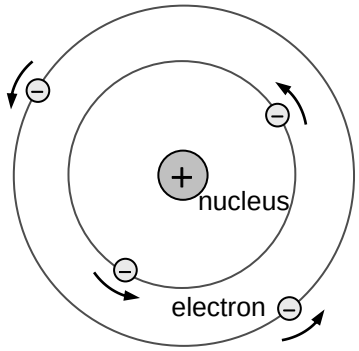
Chapter 2 Atomic Structure and Radioactive Decay

2.1 The atomic model

1 Rutherford proposed an atomic model (Rutherford's atomic model) as follows:

- All the _____ charge of the atom and most of the _____ are concentrated in a tiny core called the _____. The rest of the atom is largely _____.
- _____ orbit the nucleus.



2 Later, it was discovered that the nucleus consists of _____ and _____. Both of them are collectively called _____.

3 The table below shows the relative charge and relative mass of each type of particle in an atom.

Type of particle	Relative charge	Relative mass
proton		
neutron	0	1
electron		

4 Each kind of element has a unique atomic number (Z).

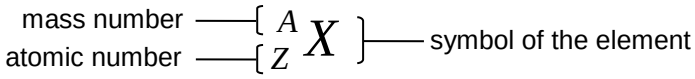
The atomic number (Z), also called the _____, is the number of _____ in the nucleus of an atom.

5 Atoms of the same element may have different masses. The masses are mainly contributed by protons and neutrons.

The _____ (*A*), also called the nucleon number, is the total number of _____ and _____ in a nucleus.

6 The _____ (*N*) is the number of neutrons in a nucleus.

7 An atom can be represented as follows:



8 A _____ is a nucleus of a particular mass number and atomic number.
A _____ is a nuclide which is radioactive.

9 _____ are different forms of the same element that contain the same number of protons (∴ same atomic number) but different numbers of neutrons (∴ different mass numbers). _____ are isotopes which are radioactive.

Checkpoint 1

Three nuclides are shown in the following table.

Nuclide	Notation	Number of protons	Number of neutrons
P	$^{12}_{4}P$		
Q	$^{12}_{5}Q$		
R		4	7

(a) Complete the table.

(b) Which of the above nuclides are isotopes?

Solution

(b)

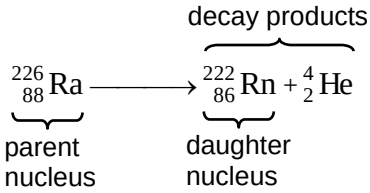
2.2 Radioactive decay

A Radioactive decay

1 Radionuclides are unstable and emit _____ spontaneously through a process called _____ or disintegration.

2 The nucleus that decays is called the _____ and the result of decay is the _____. The daughter nucleus and any particles emitted are called _____.

3 A radioactive decay can be represented by an equation. For example,

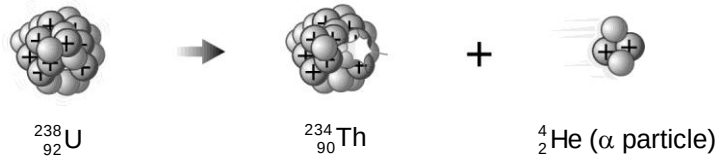


The sum of the atomic numbers (representing the charge), as well as the sum of the mass numbers, on the two sides of the equation are _____.

4 The nuclear reaction that changes the composition of the nuclide is called _____.

B Alpha decay

1 In an alpha decay (α decay), a nucleus emits an _____, which is a _____ nucleus ($^{4}_{2}He$). The following shows an example.



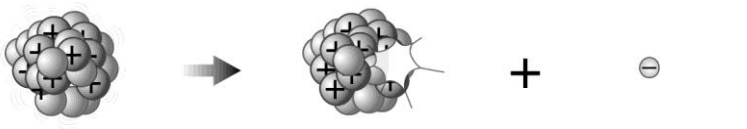
2 The general equation for an α decay is shown below:

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + \_\_\_\_\_$$

3 An α decay _____ (is / is not) a transmutation.

C Beta decay

1 In a beta decay (β decay), a neutron of a nucleus changes into a proton and an electron ($^{0}_{-1}e$) and the _____ is then emitted as a _____. The following shows an example.



$^{234}_{90}Th$ $^{234}_{91}Pa$ $^{0}_{-1}e$ (β particle)

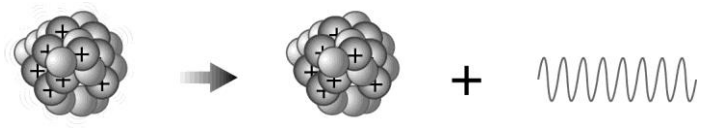
2 The general equation for a β decay is shown below:

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + \_\_\_\_\_$$

3 A β decay _____ (is / is not) a transmutation.

D Gamma emission

1 In a gamma emission (γ emission), a nucleus with more energy than normal emits the extra energy as _____. The following shows an example.



$^{60}_{27}Co^{*}$ $^{60}_{27}Co$ γ rays

2 The general equation for a γ emission is shown below:

$$^{A}_{Z}X^{*} \longrightarrow {}^{A}_{Z}X + \gamma$$

(* means that the nucleus has more energy than normal.)

3 A γ emission alone _____ (is / is not) a transmutation.

Checkpoint 2

(a) Thorium-232 undergoes an α decay. Write an equation for the decay.

(b) A radioactive nucleus emits a β particle to form thorium-228. Write an equation for the decay.

The table below shows the chemical symbols and atomic numbers of some elements.

Element	Chemical symbol	Atomic number
radium	Ra	88
actinium	Ac	89
thorium	Th	90
protactinium	Pa	91
uranium	U	92

Solution

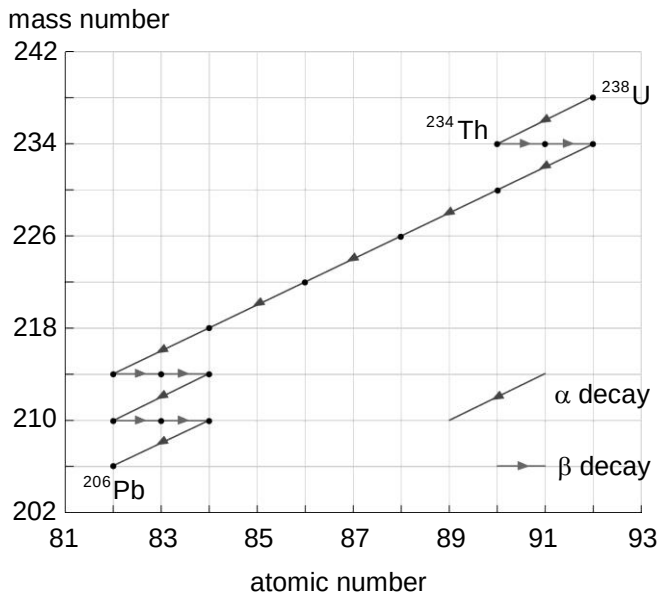
(a)

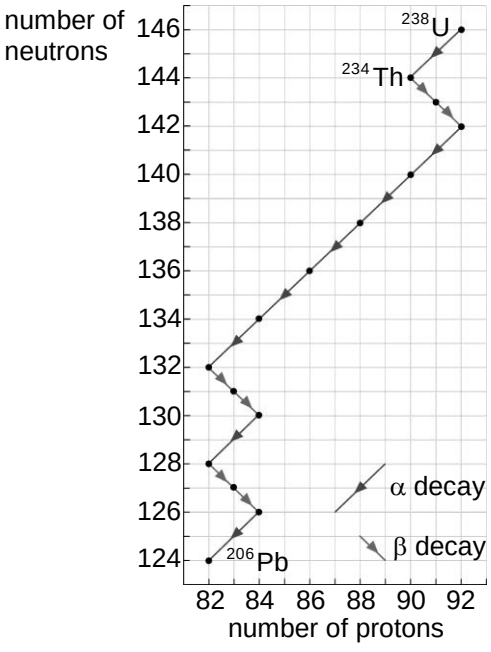
(b)

E Decay series

1 A nucleus may undergo a series of decay until a stable nucleus forms. The following equation and graphs show such a decay series. (Note that not all the decay products in each decay are shown.)

$$^{238}_{92}\mathrm{U} \xrightarrow{\alpha} {}^{234}_{90}\mathrm{Th} \xrightarrow{\beta} {}^{234}_{91}\mathrm{Pa} \xrightarrow{\beta} {}^{234}_{92}\mathrm{U} \longrightarrow \ldots \longrightarrow {}^{206}_{82}\mathrm{Pb}$$



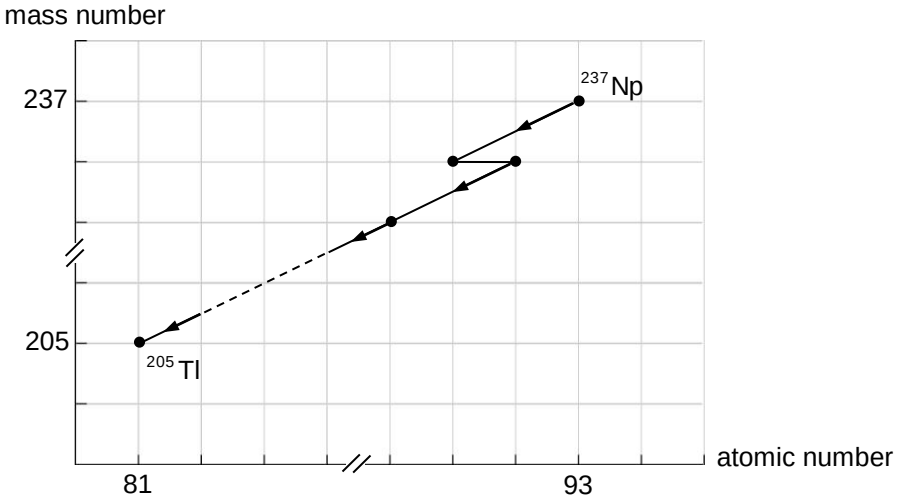


2 The mass number of the nucleus only changes in an _____ (↓ by 4), while the atomic number of the nucleus changes in an α decay (_____) and also in a β decay (_____).

Checkpoint 3

(a) A polonium-214 ($^{214}_{84}\text{Po}$) nuclide undergoes a series of decays to form nuclide *X*. In the decays, it emits two α particles and two β particles. Find the number of neutrons in *X*.

(b) A neptunium-237 nuclide decays to a thallium-205 nuclide as follows. How many α particle(s) and β particle(s) are emitted?



Solution

(a) Mass number of *X* =

Atomic number of *X* =

Number of neutrons in *X* = mass number – atomic number =

(b) Number of α particles emitted = $\dfrac{\text{change in mass number}}{\text{mass number of } \alpha \text{ particle}}$ =

Let the number of β particles emitted in the complete series be *y*.

The decay equation can be written as:

$$^{237}_{93}\text{Np} \longrightarrow {}^{205}_{81}\text{Tl} + \_\_\_\_ {}^{4}_{2}\text{He} + y\,{}^{0}_{-1}\text{e}$$

Consider the atomic numbers.

The nuclide emits _____ β particles.

F Characteristics of radioactive decay

Experiment: Radioactive decay — a dica analogy

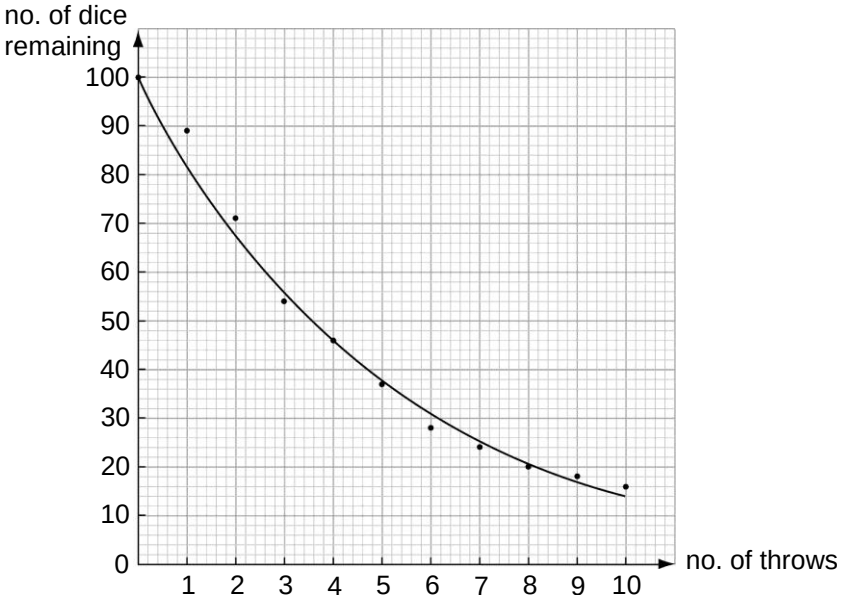
① Place 100 dice in a large box.

② Throw the dice and remove all those with side '1' facing up. Count the number of dice removed and hence find the number of dice remaining.

③ Repeat step ② with the remaining dice. Stop when only a few dice remain in the box.

④ Plot a graph of the number of dice remaining against the number of throws.

Result:



1 In the dice analogy, the dice represent _____; those with side '1' facing up represent the nuclei that have _____. The graph obtained in the dice analogy is similar to the _____ of a radioactive sample (number of undecayed nuclei against time).

2 We cannot predict which nuclei will decay at a particular time, just like we cannot predict which dice will show side '1' facing up in each throw.

Radioactive decay is _____ in nature.

3 The _____ of a radioactive sample is the number of nuclei decayed per second (rate of decay). It is measured in number of disintegrations (decays) per second (s^{-1}) or _____ (Bq).

4 The activity of a sample is _____ to the number of undecayed nuclei in a sample, i.e.

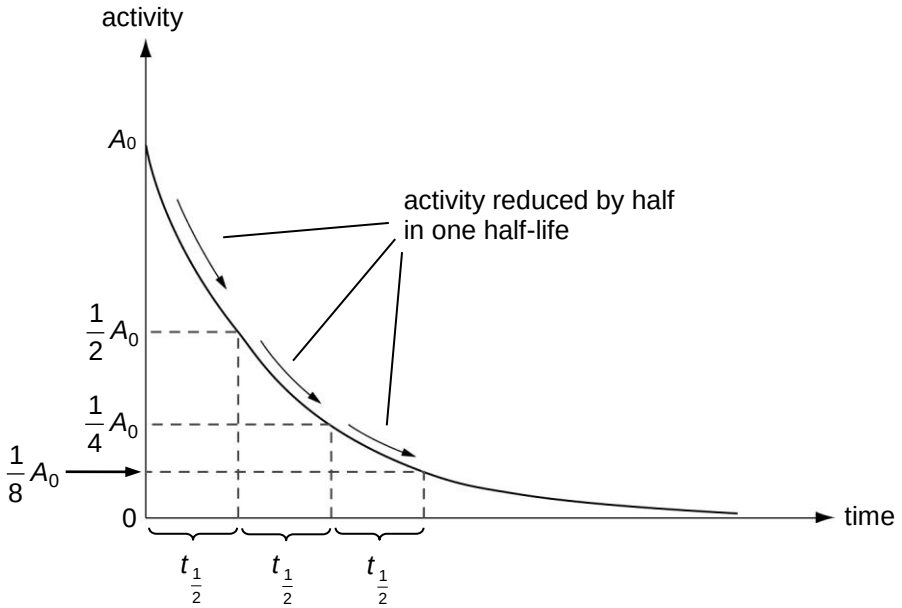
$A =$

where *k* is called the _____ with unit s^{-1}.

The decay constant (*k*) is the _____ of decay per unit time. In other words, it is the _____ of the radioactive nuclei that decay per unit time.

5 In the dice analogy, the number of throws needed for half of the 'undecayed' dice to 'decay' is a _____. In radioactive decay, the number of undecayed nuclei also halves at a regular time interval called _____.

The half-life ($t_{\frac{1}{2}}$) of a radioactive nuclide is the time taken for half of the _____ in a sample to decay. It is also equal to the time taken for the _____ of a sample to fall to half of its original value.



6 For a radioactive sample, the number of undecayed nuclei N and the activity A vary with the number of half-lives passed n as follows:

$$N = N_0 \times \left(\frac{1}{2}\right)^n \quad \textbf{and} \quad A =$$

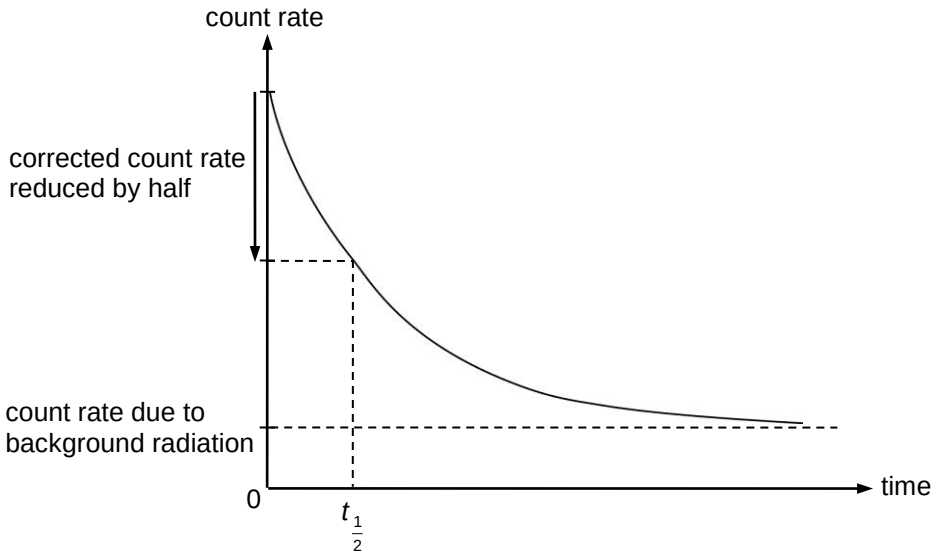
where N_0 is the initial number of undecayed nuclei,

A_0 is the initial activity.

7 Each radionuclide has a unique _____ and may vary from millions of years to less than a second. The table below shows some examples.

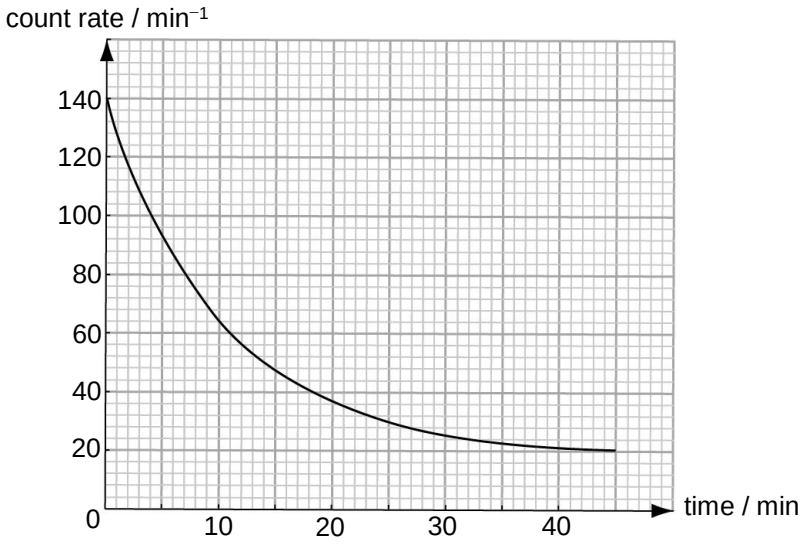
Radionuclide	Half-life
Uranium-235	7×10^8 years
Carbon-14	5730 years
Caesium-137	30 years
Iodine-131	8 days
Radon-220	56 s
Helium-5	7.6×10^{-22} s

8 When a G-M counter is used to measure the activity of a sample, the count rate measured includes the count rate due to _____. To work out the half-life of the sample, one should find the _____ (= measured count rate − count rate due to background radiation) first.



Checkpoint 4

A G-M counter is used to measure the activity of a sample. The graph shows how the measured count rate varies with time.



(a) Find the count rate due to background radiation.

(b) Find the initial count rate due to the sample (at $t = 0$). Hence estimate the half-life of the sample.

Solution

(a) Count rate due to background radiation =

(b) Initial count rate due to the sample =

Expected count rate measured after 1 half-life

= half of the initial count rate due to the sample + count rate due to background radiation

=

From the graph, the half-life of the sample is _____.

Checkpoint 5

Radon-220 has a half-life of approximately 1 minute. A sample of radon-220 has an activity of A_0. Estimate its activity after 5 minutes.

A $A_0 \times \frac{1}{5}$ B $A_0 \times \left(\frac{1}{2} \times 5\right)$ C $A_0 \times \frac{1}{2 \times 5}$ D $A_0 \times \left(\frac{1}{2}\right)^5$

Ext 9 The decay curve of a radioactive sample can be described by an exponential decay function. The number of undecayed nuclei N and the activity A vary with time t as follows:

$$N = N_0 e^{-kt} \quad \textbf{and} \quad A =$$

where N_0 is the initial number of undecayed nuclei,

A_0 is the initial activity,

k is the decay constant.

Ext 10 The half-life $t_{\frac{1}{2}}$ and the decay constant k are related by:

$$t_{\frac{1}{2}} =$$

Checkpoint 6

(a) Show that the half-life $t_{\frac{1}{2}}$ and the decay constant k of a radioactive sample are related by $t_{\frac{1}{2}} = \dfrac{\ln 2}{k}$.

(b) The half-life of radon-220 is 56 s. A sample of radon-220 has an activity of 1000 Bq. Estimate its activity after 5 minutes.

Solution

(a) Apply $N = N_0 e^{-kt}$. When $t = t_{\frac{1}{2}}$, $N =$ _____.

$= N_0 e^{-kt_{\frac{1}{2}}}$

(b) By $t_{\frac{1}{2}} = \dfrac{\ln 2}{k}$,

$k =$

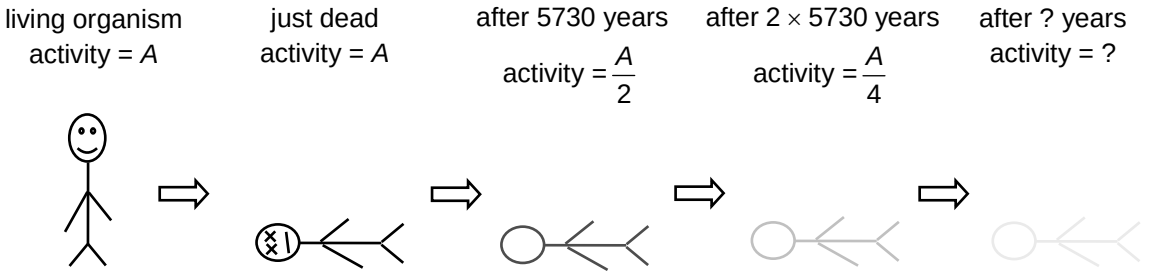
Activity A after 5 minutes $= A_0 e^{-kt} =$

2.3 Uses of radioisotopes and radiation safety

A Use of radioisotopes

1 Radioisotopes have many uses in archaeology, medicine, industry and agriculture. _____ power and _____ are important factors in making choices of radioisotopes in applications.

2 Carbon-14 dating determines the age of ancient remains by measuring the _____ of carbon-14 (C-14) contained in it. The concentration of radioactive C-14 in a living organism is _____. When the orgainism is dead, this concentration _____ with time due to radioactive decay (with half-life _____).



Checkpoint 7

A piece of ancient wood sample is examined using carbon-14 dating. It has an activity of 0.1 Bq. Another sample of the same size taken from living tree has an activity of 0.5 Bq. Estimate the age of the ancient wood sample in years. Given: 1 year = 3.16×10^7 s and half-life of carbon-14 = 5730 years.

Solution

By $t_{\frac{1}{2}} = \dfrac{\ln 2}{k}$,

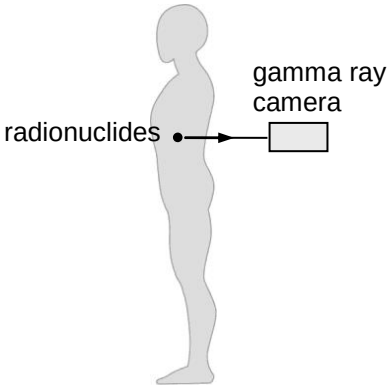
k =

By $A = A_0 e^{-kt}$,

t =

$\therefore$ The age of the ancient wood sample is _____ years.

3 Some radionuclides could be taken into a patient's body as medical tracers. By tracing the radiation emitted, abnormalities of organs in the body can be detected. These radionuclides are usually _____ (α / β / γ) sources with _____ (long / short) half-life from a minute to several days.



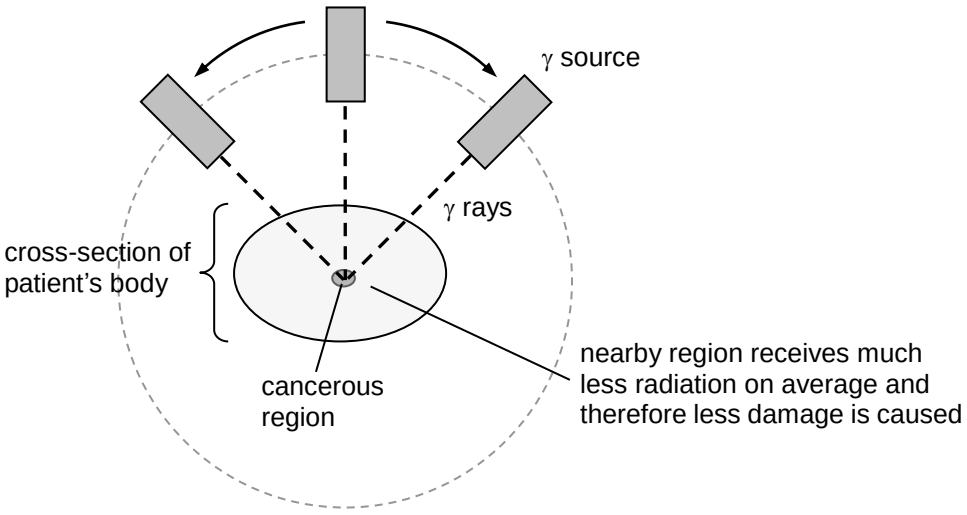
Checkpoint 8

Explain why radionuclides used as medical tracers are usually γ sources with short half-life.

Solution

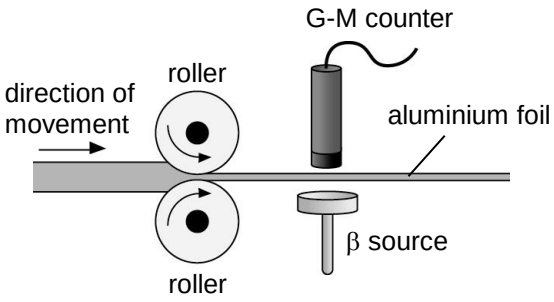
γ sources are used because γ radiation can _____ without causing much damage to the cells. They usually have short half-life so that the activity would _____ shortly after the imaging procedure.

4 Some _____ (α / β / γ) sources are used in radiotherapy to kill _____. In the treatment, a γ source is rotated around the cancerous region and emits highly concentrated γ rays to destroy the cancer cells.



5 Some other applications of radioisotopes are shown below:

(a) Thickness gauge in industry (using β radiation)

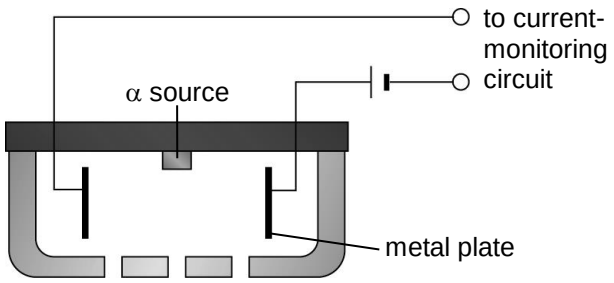


Thickness of foil changes

⇒ count rate measured due to β radiation changes

⇒ adjustment on the distance between rollers made

(b) Smoke detector (using α radiation)



In normal situation,

α radiation ionizes the air

⇒ a current flows between metal plates

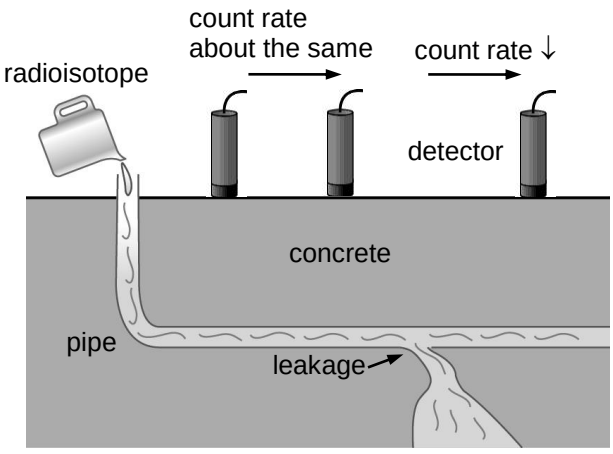
When there is smoke,

smoke particles collide with ions

⇒ current drops

⇒ alarm sounds

(c) Tracer for detecting leakage in pipes (using γ radiation)



Leakage occurs

⇒ some radioisotopes leak out

⇒ less γ radiation is detected from above the ground beyond the leak

(d) Food irradiation — kill bateria in food by γ radiation

(e) Sterilization of medical equipment by γ radiation

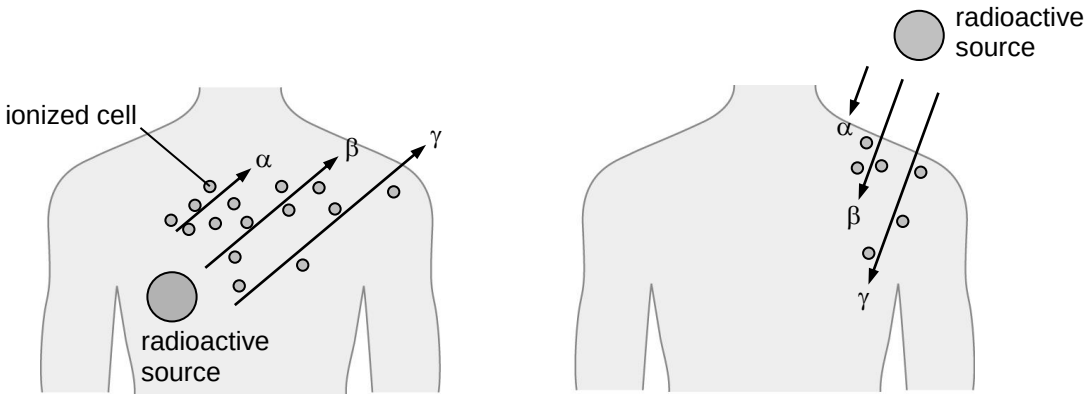
6 Ω

2 Ω

B Radiation safety

1 When a radioactive source is inside the body, _____ (α / β / γ) radiation is the most dangerous as it has the strongest _____ power.

2 When a radioactive source is outside the body, _____ (α / β / γ) radiation is the most dangerous as it has the strongest _____ power.



3 The absorbed dose indicates the amount of energy of ionizing radiation absorbed by a unit mass. The _____ is derived from the absorbed dose. It also reflects the biological effects of different types of radiation (with the weighting factor of _____ radiation 20 times that of the other types of ionizing radiation). Both the absorbed dose and the equivalent dose are measured in _____ (Sv).

4 The average annual dose from background radiation is about _____. According to the laws of Hong Kong, the annual dose limit for members of the public is _____ (excluding background radiation). An overdose may lead to extremely harmful effects. A sudden dose of 10 Sv or above is fatal.

5 Some principles for protection from nuclear radiation are listed below:

(a) Time: Minimize the exposure time to _____.

(b) Distance: Stay away from _____.

(c) Shielding: Use materials like _____, concrete and water as barriers to shield radiation.

(d) Containment: Make sure the radioactive sources are kept out of the environment.